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Curtailment of renewable electricity as a flexibility option

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About Low Carbon Ukraine

Low Carbon Ukraine is a project that continuously supports the Ukrainian government with demand-driven analyses and policy proposals to promote the transition towards a low-carbon economy. In particular, the project has the mandate to support the work of the Vice Prime Minister as he coordinates the implementation of the Energy Strategy 2035.

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Executive summary

With increasing shares of electricity generation from renewable energy source (RES), the fluctuations of RES electricity generation are increasing too. This presents a challenge to electricity system operators across the world, among them Ukraine's Ukrenergo. The need to balance these fluctuations can be addressed by adding flexible generation or storage capacity as well as demand response and transmission capacity.

We argue that temporary curtailment should be considered as another regular flexibility option in the system operator's toolbox, both in the short and long run. We show that in the short run, curtailment helps to mitigate the green-coal paradox – a situation where increasing RES shares have to be balanced by old coal plants with high minimal loads, leading to higher system emissions. Precautionary curtailment in very windy and sunny hours significantly reduces system emissions because it allows to keep nuclear units running instead of old coal plants. If 100% of renewable electricity were fed into the grid, these nuclear units would have to be shut down.

We find that using curtailment as a dispatch flexibility option allows for a nuclear electricity generation share of 57% and a RES share of 14% while reducing the thermal generation share from 56% to 24%. This altered generation mix implies a reduction of total GHG emissions from 94 to 40 Mt CO2.

We also find that 17% of potential RES electricity is unused if curtailment is implemented in the day-ahead dispatch process.

Contents

1 Introduction

With an increasing integration of renewable energy sources (RES), system operators across the world are faced with the challenge to balance the weather-dependent and thus fluctuating generation from wind and solar plants with dispatchable plants or energy storage. At the same time, the share of dispatchable plants in the system, such as coal plants, is declining due to higher RES shares.

This balancing challenge can be addressed by adding flexible generation or storage, increasing transmission capacity as well as improving demand-response abilities.

Another administrative flexibility measure is to temporarily limit the output of RES plants when the safe operation of the system is threatened or when local transmission lines cannot absorb additional electricity. This is called "curtailment".

The current discussion in Ukraine on how to deal with growing RES shares is focused on appropriate hardware solutions – i.e. introducing gas turbines and battery storage. We argue that Ukraine's electricity system must indeed become more flexible on the generation side. However, modernising plants and increasing storage capacity is only one of many flexibility options.

In many countries, curtailment of renewable energy has proven to be a "necessary evil" on the way towards a low-carbon energy system as curtailing relatively small amounts of variable renewable output makes significantly higher penetrations of RES feasible than if 100% of renewable energy were used (Yasuda et al. 2015). Once the necessary infrastructural, operational and institutional changes to increase system flexibility have been made, curtailment ratios will likely settle down (Bird et al. 2015). But even in highly flexible electricity systems, curtailment will still be the most cost-efficient option in some cases: Instead of absorbing the last kWh of a short-lived peak in wind generation with expensive storage or transmission investment, curtailing local and/or short-term generation peaks may be cheaper.

This paper focuses on the short-term effects of curtailment: We show that curtailment can help to mitigate the so-called "green-coal paradox" – a perverse increase in system emissions which can happen when a large amount of renewable capacity is added to an inflexible electricity system.

The positive effects of using curtailment as a dispatch flexibility option rely on the dynamic sizing of operational reserves, which are usually held by system operators in order to balance spontaneous imbalances in electricity supply and demand and to cover contingency events such as the loss of a large generator. We argue that these reserves should be determined dynamically for every hour of the following day, taking into account the expected infeed of RES electricity and its inherent fluctuations. We show that precautionary curtailment of renewable electricity infeed in very windy and sunny hours reduces system reserve requirements and therefore allows to keep more nuclear units on the grid – thus reducing system emissions.

This paper takes a system-optimising perspective. Our optimal dispatch model (ODM version 4.0) is able to simulate the cost-minimal dispatch of the Ukrainian power plant park taking into account the most important operational constraints (for a model description see the appendix). After finding out how the Ukrainian system could be operated in a cost-minimal manner, one needs to think about the market rules that would lead to such an optimal operation.

In this paper, we define curtailment as the temporary restriction of renewable electricity feed-in to the grid below its potential value due to operational or transmission constraints. The two most important reasons for system operators to curtail renewables are (1) to reduce actual excess supply when must-run generation and RES generation exceed demand or (2) to avoid the risk of regionally overloading the transmission or distribution network (Bird et al. 2015). This paper focuses on the first aspect – curtailment for system-wide operational security reasons.

2 Why curtailment can mitigate the green-coal paradox

A concern associated with an increasing share of renewables in Ukraine is that due to the electricity system's inflexibility, more renewables with priority dispatch could perversely increase both system-wide emissions and costs – the so-called "green-coal paradox". We argue that temporary curtailment poses the most feasible option to deal with rising shares of fluctuating renewables in the short run.

With rising RES penetration, an increasing amount of operating reserves (upwards and downwards) needs to be held in the system to be able to balance short-term fluctuations in RES generation (and load). If there is less wind and sunlight than forecasted, reserve units are ordered to increase their power generation to avoid a frequency drop. The opposite holds if RES electricity generation exceeds its forecast – downward reserves are activated, i.e. plants that are "online" are decreasing their output. Everything else equal, more renewable capacity means larger absolute forecast errors and thus larger reserve requirements.

In the Ukrainian electricity system, this could lead to a higher share of coal and a lower share of nuclear generation: In order to provide the necessary operating reserves, a large number of old coal-fired units with minimum stable loads of more than 70% have to work in the middle of their operating range (i.e., at around 85% of their capacity) to provide sufficient up- and downward flexibility. These "must-run" obligations imply that coal generation partly replaces nuclear generation, eventually leading to an increase in system-wide emissions and operating costs. However, curtailment can help to alleviate this problem in a scenario where RES deployment is faster than the installation of other flexibility options (e.g., gas turbines, batteries or demand response) – hence bridging the time gap until such investments are completed.

But also in the long run, curtailment as a regular dispatch option for the system operator can reduce the costly demand for storage to a more efficient level. The benefits of curtailment can only be fully utilised with a dynamic sizing of operational reserves through the system operator. Setting operational reserve sizes dynamically, e.g. on an hourly basis, reflects the actual demand for system operational reserves based on real-time system conditions. If system operators set a constant reserve capacity for the entire day, this constant reserve level must be able to cover the most extreme deviations of load and RES generation from their forecasts, which leads to oversized reserves for most hours of the next day and thus excessive operational costs.

When operating reserves are dynamically determined in the day-ahead dispatch for every hour of the next day, system operators can take into account the expected electricity RES generation (Srpak, Havaš & Polajžer 2019). In hours with little wind and sunlight, less reserves are thus needed. In very windy and sunny hours, on the other hand, precautionary day-ahead curtailment could make generation more predictable and hence implies that less of the expensive conventional reserves (compared to the case when 100% of RES is fed into the grid on windy and sunny days) are needed. This way, nuclear units would not have to be taken off the grid – curtailment could therefore help to mitigate the green-coal paradox. For a detailed description of how reserves are modelled see the appendix.

3 Curtailment as a regular dispatch option – a scenario comparison

3.1 Scenario setup

In the following, we employ our electricity system model of Ukraine to show the effects of using curtailment of renewable electricity in the dispatch process. We model and compare two scenarios: While in the first scenario, 100% of RES electricity is used, the second allows for curtailment of RES electricity generation in the dispatch process when system stability requirements are violated. It is important to note that these scenarios are not meant to be a 1:1 representation of Ukraine's current electricity system. Rather, they show a Ukrainian system which resembles its current characteristics but has higher RES capacities.

Our electricity system model minimises the aggregate variable electricity generation costs of the electricity system and therefore simulates the cost-optimal dispatch of Ukraine's power plant park on an hourly level. It takes into account the most important operational constraints, such as unit commitment[1] for thermal units or limited transfer capacities between TSO regions. We model a sequence of consecutive day-ahead dispatch decisions for one year: Given the trajectories of load and potential RES electricity generation, an optimal dispatch plan for the following day is developed. While a minimum of 1000 MW positive contingency reserves are held by thermal and big hydro plants for every hour of the day to be able to cover the loss of the largest generator – the so-called N-1 criterion – an additional variable amount of reserves is held based on expected solar and wind electricity generation as well as expected demand and their associated forecast errors. In the scenario with curtailment, the additional up and down reserves required due to RES generation amount to around 2.1 GW at maximum.

On the generation side, the two scenarios only differ in nuclear capacity. While in the scenario without curtailment, nuclear electricity generation is fixed at 10 GW throughout the entire year, the scenario with curtailment has nuclear generation fixed at 4 GW. While a fixed generation of 4GW has proven to be an upper bound of nuclear generation that does not yet hurt reserve requirements in our model, 10 GW represents nuclear generation shares that closely resemble the current electricity mix. Hence, this scenario setup hence aims at showing that with curtailment, keeping nuclear generation at today's level is possible even with an installed RES capacity of 7.5 GW. Without curtailment, however, the feasible share of nuclear will be much lower.

Apart from that, both scenarios are based on the 2018 demand trajectory, hourly regional wind and solar capacity factors as well as the current installed capacities of thermal, big hydro and pump storage plants. Both scenarios assume an installed total capacity of 7.5 GW of wind and solar plants. In this paper, we do not consider other flexibility options such as batteries or gas turbines. Imports and exports are neglected as well. For a more detailed overview of the scenario setup see the appendix.

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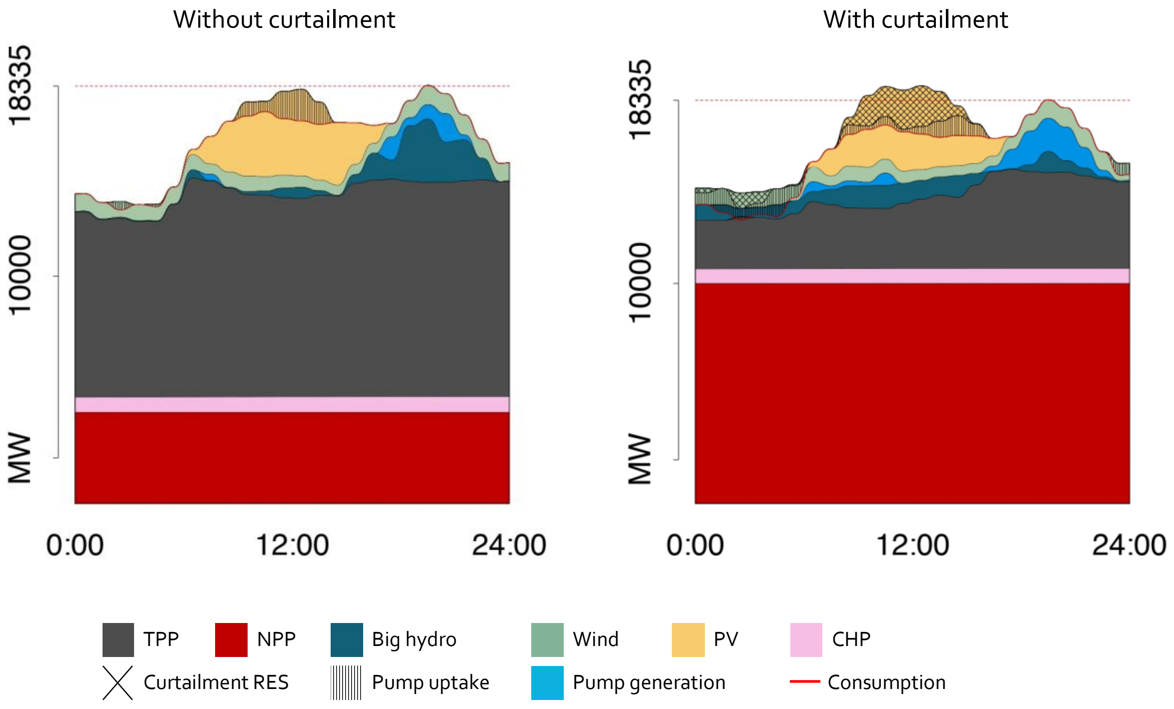
[1] Unit commitment means scheduling beforehand (e.g. a day in advance) when and which generation units to start and shut down during the operation of an electricity system over a certain time.

3.2 The effects of curtailment on dispatch

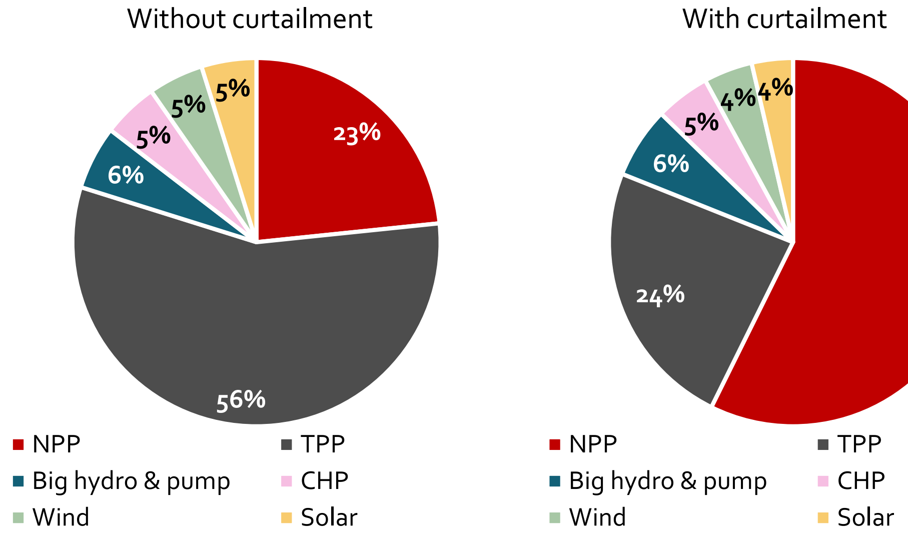
Figure 2 shows that in a scenario without curtailment of renewable electricity, thermal plants provide more than half of the entire generation throughout the year. This is due to the fact that they have to provide the operational reserve to be able to balance real-time fluctuations in renewable electricity generation. Because of the high share of thermal plants that has to be kept running, there is less electricity demand to be covered by nuclear plants. If temporary curtailment is used, however, our model results show that higher shares of nuclear – and therefore a reduction in emissions – are feasible. The dispatch charts for a working day in October under two scenarios show that for one exemplary day.

Figure 1: Dispatch chart for a working day in October



Source: own calculations

Figure 2: Annual electricity generation by technology



Source: own calculations

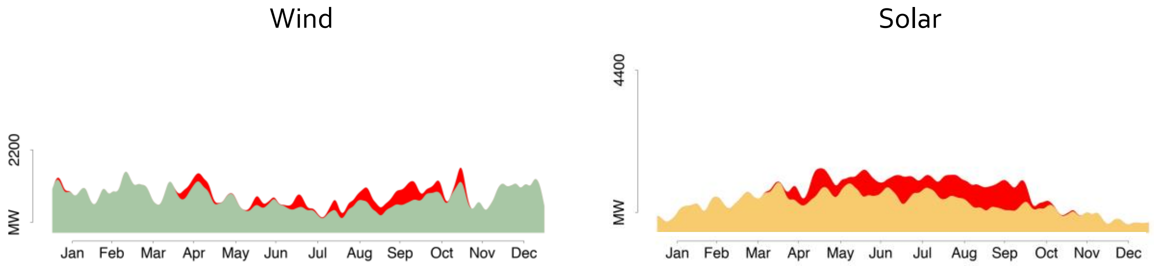
Nuclear vs. thermal generation

Introducing curtailment allows to retain a nuclear electricity generation share of **57%** while at the same time having a RES share of **14%** (i.e. hydro, wind, and solar). Moreover, thermal generation can be reduced from **56%** to **24%**. This is mainly due to the fact that in hours where solar or wind generation is curtailed, less remaining fluctuation of renewable generation needs to be covered by reserve capacities. And as these reserves are provided by big hydro and thermal plants, the more expensive thermal plants can be taken off the grid in these hours. While without curtailment, the maximum of additional reserves required is around 2.3 GW, with dispatch curtailment this number reduces to approx. 2.1 GW, leaving more demand to be covered by nuclear power plants (NPPs).

Wind and solar generation

The generation potential of wind and solar, i.e. the hourly weather conditions (wind speed and solar irradiation) for 2018, are the same for the two scenarios. However, in the scenario with curtailment, **17%** of potential electricity from wind and solar is not fed into the grid. Figure 3 shows that due to lower electricity demand, curtailment happens much more often during summer days.

Figure 3: Annual wind and solar generation and curtailment (red)[2]


Wind

Solar

Source: own calculations

While **24%** of potential electricity generation from solar is unused, only **10%** of wind electricity is curtailed. This is mainly due to the fact that on most days, the daily solar generation peak precedes the peak in demand, which can be clearly seen in Figure 1. This unfavourable combination of high RES generation potential and demand below peak levels is threatening system stability requirements – precautionary curtailment around noon therefore relieves some stress from the system.

Emissions

In the curtailment scenario, greenhouse gas (GHG) emissions are significantly lower (approx. **57%)** than in the scenario without curtailment. This reduction from 94 to 40 Mt CO2 per year is mainly due to the higher share of nuclear and a lower share of thermal generation, which is shown in Figure 3.

Finding: Curtailment reduces the necessary operating reserves and thus thermal electricity generation. Because of that, introducing curtailment leads to a significant reduction of total GHG emissions from electricity generation. In a 7.5GW RES case, emissions can be reduced by 57% through curtailment.

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[2] Hourly solar and wind generation are 4.37 GW and 2.23 GW at maximum, respectively. As these peaks are only reached in some hours of the year, the smoothed graph does not show the peaks.

4 Organising curtailment

There is a large variety in approaches and methods to curtail renewable energy. In general, one can distinguish between curtailment as an "involuntary" order from the TSO or distribution system operator (DSO) to the operator of a particular plant and "voluntary" curtailment as part of the market function – with the latter approach being increasingly popular in modern electricity systems. The traditional and centralised form of involuntary curtailment can take many forms, ranging from phone calls from system operators to RES plant operators to real-time automatic generation control systems. Technically, limiting the actual output of a wind or PV plant below its potential output is not a problem for most power plants. While for wind plants, this operational feature is built in by construction, solar plants can be equipped with a unit that enables the system operator to control its output. The German EEG, for example, states that solar plants with a capacity above 100 kW must be equipped with such a unit.

The market-based approach, on the other hand, views and values curtailment as a service to ensure system security. Its main advantage compared to centralised system operator curtailment is that economic signals concerning the cost-effectiveness of other dispatch-down options (e.g. through conventional plants) are transparent. A balancing market in which both conventional and RES producers offer (downward) reserves could therefore be more economically efficient than the centralised approach. Another advantage of market-based approaches is that they could render the compensation schemes for RES producers in cases of system operator curtailment largely unnecessary as downward reserve providers are settled at the balancing market price. However, Ukraine has only introduced its new electricity market in July 2019, and a comprehensive assessment of its functionality will need some time[3]. What is without doubt, however, is that the voluntary curtailment of RES through the balancing market is not an option for Ukraine in the short run since it requires smoothly running and more mature markets. Once there is a smoothly working balancing market in Ukraine, the option of allowing RES operators to participate should be on the table.

As curtailment is still undertaken mostly "involuntary" until today, i.e. ordered through TSOs and DSOs, the design of schemes to compensate RES producers for their lost profit is crucial to ensure incentives to invest into renewables. Although the compensation schemes greatly differ depending on a country's respective support system for renewables, most schemes have in common that the compensation is related to the foregone revenue of the plant's operation without curtailment.

Internationally applied forms of compensation include compensating the RES operator with the supported price (e.g. feed-in tariff) times the foregone production or some percentage of the wholesale market price. In some countries, RES plant operators are only compensated for losses that exceed the plant's potential production for a certain number of hours at full capacity. In general, international experience shows that most cases of curtailment are associated with wind energy, whereas solar curtailment is less common. In some countries, this has resulted in compensation schemes only existing for wind energy. The design of compensation schemes can also incentivise a better geographical distribution of new RES plants: For example, curtailing in hours with network constraints or not compensating the entire amount of foregone profit could serve as an incentive for investors to find locations with least risk of curtailment.

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[3] Low Carbon Ukraine's "Monitor of Electricity Market Opening" aims at providing regular updates on the market implementation process.

5 Curtailment in selected countries

A comparison of RES penetration and curtailment figures shows that high shares of RES are almost always associated with a certain degree of curtailment. One could argue that high shares of renewables inevitably lead to curtailment. However, the more accurate reasoning is that without the possibility of temporary curtailment, integrating high RES shares becomes very expensive.

While some countries, including Germany, still prefer to implement curtailment through DSOs and TSOs, other countries such as Denmark have made the dispatch-down of RES a part of the regular balancing market. A market-based approach might be economically most efficient as the compensation for dispatching down RES is determined through the interaction of supply and demand for electricity rather than a lump sum compensation. The following Table 1 shows curtailment (as a share of total wind/solar generation) and wind/solar penetration (RES electricity generation/total demand) for selected countries.

Table 1: Wind and solar curtailment & penetration for selected countries in 2017

Country	Total production, TWh	Wind penetration	Solar penetration	Wind curtailment	Solar curtailment
China	6313	5%	2%	12%	6%
Germany	654	18%	7%	5%	<1%
Ireland	31	26%	-	4%	-

Sources: China National Renewable Energy Centre, Bundesnetzagentur, BMWi, Statistisches Bundesamt, Eirgrid, SONI, seai

China

The high levels of curtailment in China can be explained by the rapid expansion of renewable capacity, a suboptimal geographic distribution of load centres and renewable energy generation as well as insufficient transmission capacity. Must-run obligations for coal plants, a lack of flexible generation capacity and the need to keep CHPs generating for district heating in winter are further aggravating factors. To address these challenges, China aims to implement a number of measures such as an improved forecasting system and the connection of RES plants to automatic generation control systems (Bird et al. 2015).

Germany

In Germany, 96% of curtailed electricity was wind electricity in 2017. This is likely due to the fact that most solar is connected at the low-voltage level, while curtailment occurs at the high and medium-voltage level. Curtailment figures have risen rapidly in recent years because the expansion of grid capacity lags behind the deployment of renewables. From 2009 to 2017, RES curtailment has increased from 74 to 5518 GWh.

Ireland

Ireland, which has no significant solar generation, shows that even with a high penetration of renewables, modest levels of curtailment are achievable. In 2017, where wind plants covered 26% of electricity demand, only 4% of total available wind energy was curtailed. While 31% of curtailment was due to network reasons such as excesses of grid capacity or maintenance outages of transmission lines, 69% were due to system stability requirements, operating reserve requirements or voltage control requirements. The latter type of curtailment typically occurs in times of low electricity consumption from 11pm to 9am when minimum generation levels are imposed on conventional plants, whereas curtailment due to local network "congestion" is more likely throughout the day (EirGrid & SONI 2018).

6 Outlook

In this policy paper, we have shown that curtailment of renewable electricity as a regular flexibility option for system operators allows to mitigate the green-coal paradox in Ukraine. By reducing the reserve requirements in hours with precautionary day-ahead RES curtailment, less thermal units need to be held as operating reserve. This in turn allows to increase the feasible share of nuclear electricity generation, leading to an overall decline in GHG emissions from electricity generation.

The aim of this paper is to show that temporary curtailment of renewable electricity generation serves as a "necessary evil" because it adds to a system operator's toolbox as an additional flexibility option. Whether this flexibility option is not only a short-term solution to the green-coal paradox but also a regular alternative to other hardware flexibility options depends on economics: With a transparent and well-designed compensation scheme for RES producers, it is possible to ensure both investment incentives and a cost-minimal operation of Ukraine's electricity system with minimal curtailment rates. A following step would be to think about market rules that lead to such an optimal behaviour of market participants. Allowing RES producers to participate on the balancing market is one interesting option to consider.

The results derived in this paper are dependent on the system operator's ability to dynamically set reserve requirements. We have shown that precautionary curtailment of renewable electricity infeed in very windy and sunny hours reduces system reserve requirements and therefore allows to keep more nuclear units on the grid. We therefore argue that reserves in the Ukrainian electricity system should be determined dynamically, taking into account the expected infeed of RES electricity and its associated forecast errors. Within the framework of this policy paper, the question of how to optimally design Ukraine's operating reserves could only be discussed briefly. Subsequent – and more detailed – work on the adequate dynamic sizing of operational reserves would provide an important contribution to making Ukraine's electricity system future-proof.

7 Appendix

7.1 Parametrisation and aggregated results

Table A 1: Installed capacities, MW

Type	With curtailment	Without curtailment
Wind	2,250	
Solar	5,250	
NPP	10,000	4,000
TPP	16,460	
Big hydro	4,600	
Pump storage	1,500	

Source: own calculations

Table A 2: Aggregated results

	Without curtailment	With curtailment
(1) Electricity generation	TWh	
NPP	35.0	87.6
TPP	84.7	36.3
Big hydro	7.6	6.8
CHP	7.3	7.3
Pump generation	0.7	2.7
Wind	7.3	6.6
Solar	7.2	5.5
(2) Curtailment	TWh	
Wind	–	0.73
Solar	–	1.71
(3) Emissions	94 Mt CO2	40 Mt CO2

Source: own calculations

7.2 Model description

The optimal dispatch model (ODM) was developed within the Low Carbon Ukraine project and is currently available in version 4. We considered state-of-the-art energy economic mathematical formulations for the implementation of the ODM. The model was implemented in Pyomo, a Python-based, open-source optimisation modelling language. Pyomo allows to use different open-source (e.g. CBC or GLPK) as well as commercial solvers (such as GUROBI, CPLEX or MOSEK). Input data used for the model either represents current technological and economic characteristics of Ukraine's electricity sector or – if not available – are based on scientific literature.

7.2.1 Motivation

The ODM allows to analyse scenarios of the potential long-term developments of the Ukrainian electricity system regarding:

- Their technical feasibility,
- Potential bottlenecks in generation and/or transmission,
- Their respective power generation costs and
- Associated carbon intensities of electricity generation.

Based on scenario results, policy-makers can be informed on potential RES development pathways, associated investment needs and prices as well as welfare effects.

7.2.2 Characteristics

We follow an optimisation approach, meaning that the model minimises the aggregated power generation costs under a set of technological constraints. For each hour, the model defines the required amount of electricity generation based on the technological characteristics of all power plant types so that demand is covered and all further constraints are met.

The model gives day-ahead dispatch decisions, i.e. it optimises 24-hour time spans.

Time frame: The model optimises one year of 8760 hours.

Technologies: We consider nuclear and thermal capacities as well as wind, solar, pump hydro and big hydro capacities. Furthermore, CHP is modelled as an exogenously given power generation trajectory for 2018.

Regions: The model considers 8 TSO regions that are connected via net transfer capacities. The aggregated load per hour for the sum of all regions follows the 2018 load trajectory for Ukraine.

Transmission: TSO regions are connected by no more than one interconnector. We assumed net transfer capacity between regions based on the estimated aggregate capacities of high-voltage transmission lines. The balance rule in each TSO region as well as Kirchhoff laws are modelled.

Uncertainty: The present model version follows a probabilistic (unit commitment) paradigm – an expansion of the deterministic approach, which is "the most common practice used for dealing with uncertainty in the power industry" (Morales-Espana 2014, p. 28).

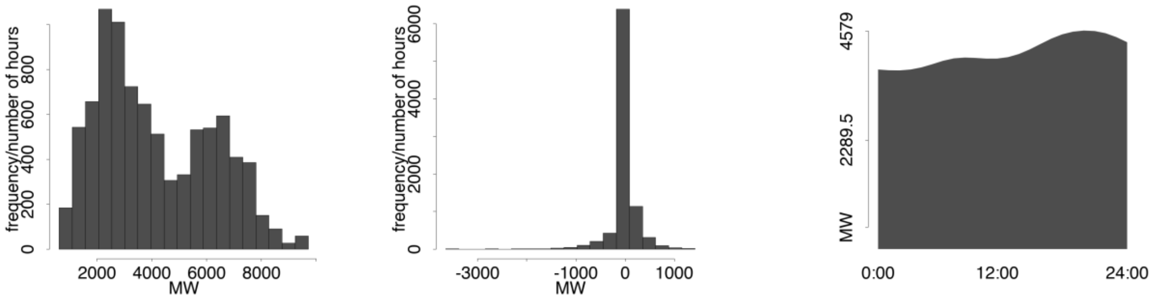
RES and demand fluctuations as well as the risk of conventional power plant outages (N-1 criterion) are taken into account by the model's reserve sizing algorithm (see below). Unlike to the stochastic and the robust unit commitment paradigm, the deterministic paradigm requires less computational power and is easy to implement. Yet, it typically overestimates the necessary reserves, which is economically inefficient (Morales-Espana 2014).

7.2.3 Generation capacities

TPP characteristics

The model uses 16.4 GW of thermal capacities located in the different regions. The present model version implements deterministic unit commitment for TPPs. This way, TPP units of the same type are aggregated to unit clusters. Each physical TPP unit can either be switched on or off, is in start-up or shut down mode. For all TPP units, ramping constraints during normal operation as well as start-up and shut-down time (when 50% of unit capacity is available), minimal down- (10 hours) and up-time (5 hours) as well as minimal loads (between 50 and 70%) are modelled (Meus, Poncelet & Delarue 2017).

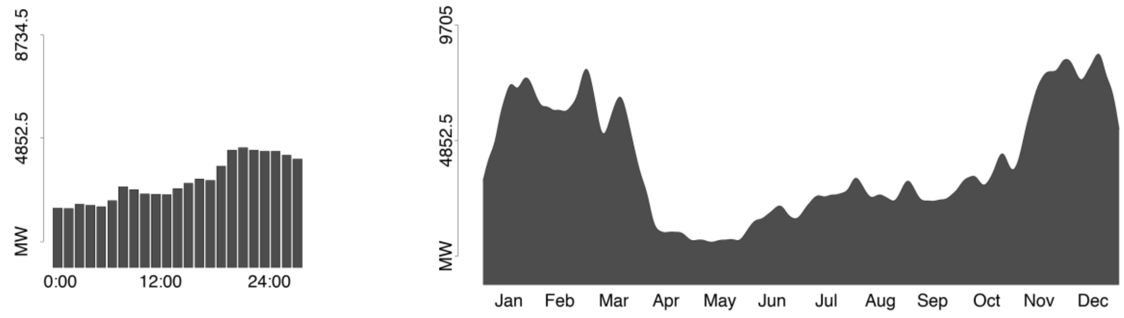
Figure A 1: Exemplary results for TPP generation in a 7.5 GW RES scenario



Histogram of hourly TPP load

Histogram of hourly TPP load changes

24h averages of TPP load



Hourly TPP load for October 1

Annual trajectory of TPP load

NPP characteristics

In the present model version, NPP capacities are must-run generators without ramping capability.

Big hydro characteristics

In Ukraine, eight big hydro power plants are in operation. Seven big hydro plants located at river Dnepr are arranged in a cascade of reservoirs and run-of-river plants. Moreover, two dam hydro plants are located at river Dniester. The installed capacity of big hydro plants sums up to 4.6 GW. In our model, each power plant at the river Dnepr has a reservoir for storing water. The different reservoirs are either located directly in front of a power plant or on the river between two plants. The power generation potential of each big hydro PP depends on the available upstream water flow and the plant characteristics such as hydraulic head, generator discharge and installed capacity[4]. The annual river discharge for both rivers is approximated based on available data (Kara et al. 2008). The respective stock change of water reservoirs is modelled as well.

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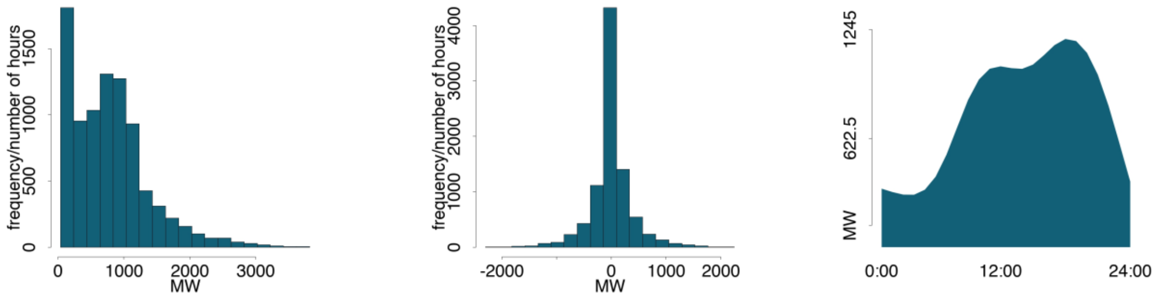
[4] Plant characteristics are provided online by Ukrhydroenergo (http://uhp.kharkov.ua/en).

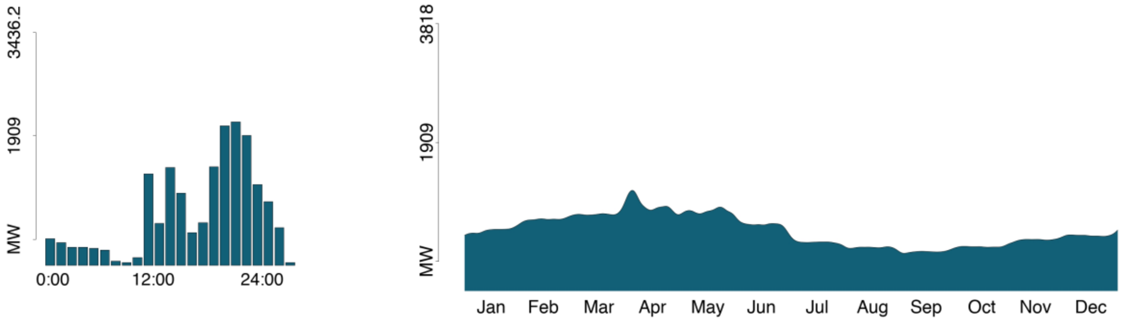
Figure A 2: Exemplary results for big hydro generation in a 7.5 GW RES scenario



Histogram of hourly BH load

Histogram of hourly BH load changes

24h averages of BH load



Hourly BH load for December 1

Annual trajectory of BH load

Pump hydro characteristics

We consider 1.5 GW of pump capacity in generation mode and an associated storage capacity of 7 GW. For simplification, we describe the storage process as storage of electricity instead of water. A conversation efficiency of 73% is assumed for all pumps.

RES characteristics

The model accounts for wind and solar generation. For each region, we model aggregated "unit" of wind/solar parks. The installed capacities in each region are exogenously determined.

Power generation is constrained by weather-dependent variables. Fluctuations are represented by hourly capacity factors resulting from wind speed and solar irradiation changes in each region. We use data provided by Renewables.ninja[5].

7.2.4 Reserve sizing

The present model follows a probabilistic approach. Unit commitment and dispatch have to meet (expected) load, while uncertainty is handled by operating reserves. (For a comparison of unit commitment approaches see e.g. Lowery & O'Malley (2014) and Morales-Espana (2014)). Our (probabilistic) approach takes into account RES power forecasting errors (Magdkowski & Kaltschmitt 2017). Unlike the stochastic and robust unit commitment approach we do not consider the uncertainty of RES electricity generation directly (Zhou et al. 2016). Therefore, reserve requirements result from uncertainty regarding RES generation and demand forecast errors as well from the N-1 criterion. We do not distinguish between secondary, primary and tertiary reserves and combine them in one figure.

The determination of up and down reserves takes place through a "dynamic scheduling of regulating power" (Srpak et al. 2019). A change in the expected value of an underling uncertainty (RES fluctuation)

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[5] https://www.renewables.ninja

results in a change of the required reserves. Therefore, reserve requirements may change from hour to hour.

While down reserves cover an unforeseen increase of (typically RES) electricity generation or a decline in demand, up reserves provide flexibility in cases where the generation breaks down (either through lower RES generation or additionally through the outage of a conventional generator) and/or unforeseen demand surges. Both up and down reserve requirements consist of a fixed and a variable share. With a fixed share of 1 GW up reserves the N-1 criterion is addressed.

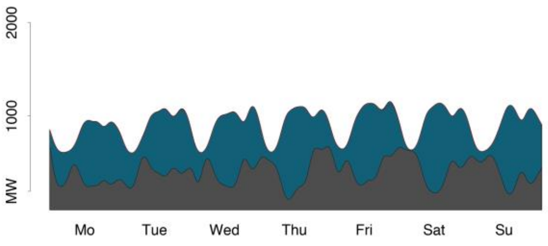
The variable share of reserve covers the errors of wind, solar and demand forecasts. Hence, the (variable) part of reserves is determined based on the expected value (forecast) of wind and solar generation and demand plus a risk surcharge that considers non-structural and non-biased errors of forecasts. The risk surcharge is determined based on the distribution of forecast errors and an exogenously given risk-taking. For the sake of simplification and due to computational limitations of the open source solver (GLPK), the forecast errors are assumed to follow a normal distribution with mean zero and a standard deviation sigma for each generation type and demand (For a discussion of the distributional characteristics of forecast errors see Hodge et al. 2012). For this paper we assume a standard deviation sigma of 20% and 15% for wind and solar relative forecast errors, based on data for Germany, and for demand of 2%. For a further evaluation of reserve requirements, a detailed analysis of Ukrainian wind and solar forecasts is needed.

Example: Assuming a forecast of wind and solar generation at 12am of 2 GW, 1 GW respectively and a demand forecast of 22 GW, the standard deviation sigma is given by

$$\sqrt{(0.2\cdot 2\,GW)^2 + (0.15\ \cdot 1\,GW)^2 + (0.02\cdot 22\,GW)^2} = 0.61\,GW.$$

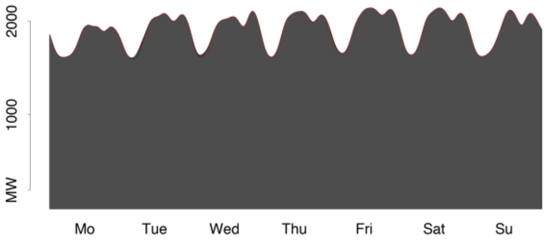
Using a confidence interval of 95% (2.5 sigma), the variable reserves would then be 1,533 MW.

Figure A 3: Up and down reserves for one week in a 7.5 GW RES scenario



Down reserves by providing generator type

■ TPP ■ Big Hydro



Up reserves by providing generator type

■ TPP ■ Big Hydro

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